



**UNIVERSITY OF
TECHNOLOGY SYDNEY**

SCHOOL OF LEISURE, SPORT & TOURISM

Neuromuscular and functional adaptations to whole body vibration exercise in older adults

Sven S. Rees

BA (Human Movement Studies) (Hons)


This thesis is submitted to fulfill the requirements for the degree of Doctor of
Philosophy at the University of Technology, Sydney, September, 2008.

Certificate of Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written solely by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of candidate



Acknowledgements

There are so many people I would like to acknowledge for their support, help and friendship over the course of this thesis. I would like to first acknowledge Dr Aron Murphy. Thank you so much for your supervision. I am extremely grateful for all your assistance, expertise, and reviewing skills; but above all your sense of humor.

To my co-supervisor Mark Watsford, thank you for all the time that you dedicated to reviewing and providing feedback for this thesis. I thank you for always being available, being a spring board for ideas, listening to my many blow ups and providing many of your own. You have made this whole process an extremely enjoyable one.

I would like to thank everyone who provided assistance along the way. Thanks must go to Kanchana Gamage for his help organizing laboratory equipment, driving participants to and from Narrabeen and for always being a larrikin. Thank you to Professor Maria Fiatarone Singh for providing advice on study one's methodology. To Ron Thomson and Professor Tracey McDonald for letting me come into their retirement village and conduct research. To Lyn Mayer for her helping recruit subjects and going out of her way to accommodate me. To all the participants who volunteered, this thesis would not have been possible without your help and dedication.

To all the UTS staff and fellow post graduate students who have made this an extremely enjoyable process. To Lee Wallace, Katie Slattery, Ken McLachlan, Dan Lock, Matt Pine, Bob Lockie, Rob Spurrs, Anthony Whitty, Aaron Coutts, Brendan Inkster, Alexandra Fentoullis, Rob Bower, Yvette Wainwright, Kylie Hunter, Sera Dogramaci and Kylie Johnson. While I needed no help procrastinating, you have all assisted me in this skill and provided many laughs along the way.

A large thank you to all my friends who have tolerated my preoccupation with this thesis. Whenever I needed an escape from work you guys were always there.

Finally, to my parents: To Mum who tirelessly looked after me. To Dad, who was always available to proof read my work at the drop of a hat. Thank you for allowing me to be a “KIPPER.”

Dedication

This thesis is dedicated to Mum and Dad.

Abstract

The ageing process is associated with sarcopenia; a reduction in muscle mass, strength and power. Sarcopenia is responsible for diminished physical performance; it affects the ability to perform activities of daily living and can severely impact quality of life in older age. There is potentially no age group that can benefit more from interventions to combat reduced muscle strength and power than an older population. Whole body vibration (WBV) is a relatively new exercise intervention. WBV is suggested to improve strength and power by stimulating the neuromuscular system and inducing reflex muscle contractions. The potential for WBV to be used as a strength training intervention for an older population was the rationale behind this thesis.

Study one was an investigation of the effects of eight weeks WBV on a range of physical performance measures in a healthy, older population. Forty three, older adults (73.5 ± 4.5 yr, 168.2 ± 10.5 cm, 74.5 ± 11.1 kg) were divided into three groups: 15 to a WBV group (VIB), 13 to an exercise without vibration group (EX) and 15 into a control group (CONT). The VIB and EX group interventions consisted of three sessions per week for eight weeks. Outcome measures included isokinetic flexor and extensor strength of the hip, knee and ankle, one-legged postural steadiness (OLPS), sit-to-stand performance (STS), fast walk time and stair mobility.

Following the eight week intervention, the VIB group significantly improved OLPS compared to the EX and CONT groups ($p < 0.05$). The improvements in OLPS were

significantly affected by baseline values, with the largest changes evident for VIB participants with a poorer initial score ($p < 0.01$). WBV exercise can improve OLPS in a healthy, older population. As improvements in OLPS were related to baseline values, WBV as an intervention would appear to serve the most benefit for those that exhibit diminished postural control.

The VIB group significantly improved ankle plantar flexor strength compared to the EX and CONT group (18.2%, 5.0%, 0.9%) ($p < 0.05$). The VIB and EX groups both significantly improved knee extension strength compared to the CONT (8.1%, 7.2%, -2.0%) ($p < 0.05$). There were no effects for hip flexor or extensor strength. The VIB and EX groups both showed improved STS (12.4%, 10.2%) and 5m fast walk (3.0%, 3.7%) compared to the control ($p < 0.05$). There were no effects for stair mobility performance. While WBV exercise can be considered a plantar flexor strength training intervention, it appears to have a disproportional effect on lower limb strength. WBV did not facilitate knee extensor strength or physical performance measures to a greater degree than the same exercise program without vibration. The comparable change in physical performance measures between the VIB and EX groups appears linked to similar gains in knee extensor strength. Further, these similar knee extensor strength improvements appears linked to the same body weight squats performed by both the VIB and EX groups.

To explore the disproportional change in lower limb strength found in study one, study two was designed to investigate the neuromuscular activation of the ankle, knee and hip flexors and extensors during WBV. Ten healthy, older male participants (70.4 ± 4.9 yr, 176.9 ± 7.8 cm, 78.6 ± 12.0 kg) completed a number of static exercises with

and without WBV. Activation of the soleus, gastrocnemius, tibialis anterior, vastus medialis, rectus femoris, biceps femoris, iliopsoas and gluteus maximus were recorded unilaterally with electromyography (EMG). EMG amplitude was normalised and analysed with respect to each individual's maximum isometric strength values. The absolute increases in EMG with vibration, above the non-vibration condition, were compared between muscle groups and exercise conditions. The increase in neuromuscular activity with WBV was significantly larger in the soleus and gastrocnemius than muscles higher up the leg ($p < 0.05$). Furthermore, the increase in gastrocnemius neuromuscular activity was greatest when participants maintained a heel raise position. It appears that WBV should be prescribed as an exercise intervention that intends to specifically train the triceps surae musculature.

The results of study one and two suggested WBV be considered a localised strength training intervention for older individuals which predominately targeted the plantar flexors. The aim of study three was to examine the efficacy of WBV for a frail, elderly population; to validate plantar flexor strength improvement with WBV and examine the neuromuscular mechanisms associated with this adaptation. Seventeen frail, older participants (88.2 ± 3.6 yr, 166.8 ± 8.2 cm, 71.7 ± 11.4 kg) were divided into two groups: ten to a WBV group (VIB) and seven to a control group (CONT). The VIB group undertook WBV three times per week for four weeks. Outcome measures included isometric and isokinetic plantar flexor strength, single leg balance performance and EMG of the gastrocnemius. The EMG signal was analysed for amplitude and median power frequency. EMG amplitude was normalised with respect to each individual's maximum isometric strength values.

WBV had no effects on single leg balance performance in a frail, older population. This result is in contrast to study one that found significant improvements in OLPS in a population of healthy, older adults. In contrast to study one participants, the frail older adults in study three were unable to exercise on the WBV platform without firmly grasping the handlebars for support. The difficulty maintaining balance whilst undertaking WBV exercise is suggested to be a mediating factor behind the improvements in balance observed in study one but not three.

Following the WBV intervention, the VIB group significantly improved isometric (40.5%) and isokinetic (32.4%) plantar flexor strength compared to the CONT group (1.5%, 2.9% respectively) group ($p < 0.05$). The WBV group displayed a significant 32.3% increase and a 8.3% decrease in right medial gastrocnemius EMG peak amplitude and EMG median power frequency respectively during isometric plantar flexion ($p < 0.05$). WBV can be considered an effective training intervention to improve plantar flexor strength in frail, older adults. It is speculated that increased plantar flexor strength with WBV exercise be explained at least in part by an improvement in motor unit synchronisation and efficiency.

KEYWORDS: Ageing, whole body vibration, exercise, strength training, balance.

Table of Contents

Certificate of Originality	ii
Acknowledgements	iii
Dedication	v
Abstract.....	vi
Table of Contents	x
List of Tables	xv
List of Figures.....	xviii
List of Abbreviations	xxii
List of Publications	xxiv
Conference Presentations.....	xxiv
 CHAPTER 1: INTRODUCTION.....	 1
1.1 Background.....	2
1.2 Statement of the problem.....	7
1.3 Research hypothesis	8
1.4 Significance of the study	9
1.5 Delimitations	11
1.6 Limitations.....	11
1.7 Summary.....	12
 CHAPTER 2: REVIEW OF LITERATURE.....	 13
2.1 Overview	14
2.2 The ageing population	15
2.3 Functional anatomy and physiology of the muscular system.....	24

2.4	Effects of ageing on the functional and physiological performance of the muscular system	34
2.5	Exercise and the older population	46
2.6	Whole body vibration exercise	61
CHAPTER 3: METHODS – STUDY ONE		89
3.1	Overview	90
3.2	Participants	90
3.3	Testing procedures.....	92
3.4	Reproducibility of measurements	103
3.5	Data analysis	104
CHAPTER 4: RESULTS – STUDY ONE		106
4.1	Overview	107
4.2	Physical characteristics	108
4.3	Adherence to training	109
4.4	Isokinetic strength and power tests.....	112
4.5	Muscle strength interactions	120
4.6	Functional performance measures	122
4.7	One-legged postural steadiness	127
4.8	Summary of significant findings following the training period	131
CHAPTER 5: DISCUSSION – STUDY ONE.....		133
5.1	Overview	134
5.2	Isokinetic strength and power	136
5.3	Functional performance measures	142
5.4	One-legged postural steadiness	149
5.5	Summary	154

CHAPTER 6: METHODS – STUDY TWO	157
6.1 Overview	158
6.2 Research hypothesis	158
6.3 Significance of the study	159
6.4 Delimitations	160
6.5 Limitations	161
6.6 Participants	161
6.7 Treatment Protocol	162
6.8 Electromyography	164
6.9 Testing procedure	171
6.10 Data analysis	173
CHAPTER 7: RESULTS – STUDY TWO	174
7.1 Overview	175
7.2 Physiological Characteristics	176
7.3 Negative response to vibration stimulus	176
7.4 Increased neuromuscular activation as a result of vibration between muscles during the same exercise	177
7.5 Average change in neuromuscular activation between muscles across all exercise conditions as a result of vibration	178
7.6 Increased neuromuscular activation as a result of vibration between exercises for each individual muscle group	181
7.7 Summary of significant findings	183
CHAPTER 8: DISCUSSION – STUDY TWO	186
8.1 Overview	187
8.2 Neuromuscular activation between distal and proximal muscles of the lower limbs resulting from vibration	187

8.3	Vibration induced neuromuscular activation between static body positions.....	189
8.4	Conclusion.....	193
CHAPTER 9: METHODS – STUDY THREE.....		194
9.1	Overview	195
9.2	Research hypothesis	196
9.3	Significance of the study	196
9.4	Delimitations	197
9.5	Limitations.....	198
9.6	Participants	198
9.7	Testing procedures.....	200
9.8	Data analysis.....	208
CHAPTER 10: RESULTS – STUDY THREE.....		210
10.1	Overview	211
10.2	Physical Characteristics.....	212
10.3	Response to whole body vibration exercise	212
10.4	Isometric plantar flexor and dorsi flexor strength	216
10.5	Isokinetic strength and power.....	217
10.6	Electromyography	219
10.7	Single leg timed balance.....	222
10.8	Correlations	224
CHAPTER 11: DISCUSSION – STUDY THREE.....		225
11.1	Overview	226
11.2	Plantar flexor strength and power.....	227
11.3	Neuromuscular activation patterns.....	232

11.4	Single leg timed balance.....	238
11.5	Response to whole body vibration exercise	241
11.6	Summary.....	245
CHAPTER 12: SUMMARY AND RECOMMENDATIONS.....		246
12.1	Overview	247
12.2	Major findings	248
12.3	Directions for future research	250
REFERENCE LIST.....		253
APPENDICES		289

List of Tables

Table 2.1 - Age categories	18
Table 2.2 - Characteristics of human skeletal muscle fiber types.....	28
Table 2.3 - WBV effects on muscular performance.	73
Table 2.4 - The effects of WBV in an older population.	76
Table 3.1 – Study one training volume and intensity.	102
Table 3.2 – Intra-day reliability of the dependant measures.....	104
Table 4.1 – Physical characteristics for all participants.....	108
Table 4.2 – SF-36v2 Health Survey.....	110
Table 4.3 – Hip flexor and extensor strength and power.	113
Table 4.4 – Knee flexor and extensor strength and power.	114
Table 4.5 – Ankle dorsi flexor and plantar flexor strength and power.	118
Table 4.6 – Timed up-and-go test.	122
Table 4.7 – The fast walk test.	124
Table 4.8 – Sit to stand test.....	126
Table 4.9 – Results from stair mobility performance for all participants.....	127
Table 4.10 - One legged postural steadiness results for the vibration, exercise and control groups.....	129

Table 4.11 – Summary of significant between group interactions.	132
Table 6.1 – Joint angles during isolated maximum voluntary contractions.	163
Table 6.2 – Joint angles for each exercise condition.	164
Table 7.1 – Physical characteristics for all participants.....	176
Table 7.2 – Changes in neuromuscular activation relative to MVC during WBV above the non-vibration condition.	180
Table 9.1 – Study three WBV training program (3 sessions per week).	208
Table 10.1 – Physical characteristics for all participants.....	212
Table 10.2 –WBV prescription variables reduced intensity for two participants.....	215
Table 10.3 – Isometric strength results from the ankle plantar flexors and dorsi flexors for all participants.	216
Table 10.4 – Isokinetic strength and power results from the ankle plantar flexors and dorsi flexors for all participants.	218
Table 10.5 – Peak muscle activity percentage changes of the gastrocnemius and tibialis anterior during maximal isometric and isokinetic exercises following four weeks training for all participants.	220
Table 10.6 – EMG median frequency activation properties of the gastrocnemius and tibialis anterior during a maximal isometric contraction following four weeks training for all participants.	221
Table 10.7 – Relative antagonist co-contraction torque and neuromuscular activation coordination between the antagonist and agonist during isokinetic dynamometry. ...	222
Table 10.8 – Results from the single leg timed balance test for all participants.	223
Table 10.9 – Calf muscle activity during the single leg timed balance test for all participants.	223

Table 10.10 – Correlations between age, single leg balance and plantar flexor strength
for all participants. 224

List of Figures

Figure 2.1 – The changing age structure of Australia’s population for the period between 1983-2003 by age and gender.....	16
Figure 2.2 – Population projections for Australia by age group and gender, 1999 – 2051.....	16
Figure 2.3 – Vicious cycle of sarcopenia and physical activity.....	22
Figure 2.4 – The summation of neural impulses leading to increase force output.	26
Figure 2.5 – Relative roles of neural and myogenic adaptations to resistance training.....	30
Figure 2.6 – Multiple factors that cause loss of muscle strength with increasing age.....	35
Figure 2.7 – Maximal voluntary torque of ankle dorsi flexor and plantar flexor muscles in males and females of different ages	36
Figure 2.8 – Relationship between age and total number of fibers.	37
Figure 2.9 – Relationship between age and muscle area	38
Figure 2.10 – Prolongation of muscle twitches of ankle plantar flexors	40
Figure 2.11 – Mean free testosterone index (the ratio of serum total testosterone to sex hormone-binding globulin levels) during the lifespan of healthy men	42
Figure 2.12 – Insulin like growth factor changes in healthy women (left) and men (right) during the ageing process.....	44
Figure 2.13 – A comparison of general level of physiological function between active and sedentary individuals across the lifespan	47
Figure 2.14 – The reflex arc in the elicitation of the tonic vibration reflex.....	61

Figure 2.15 – Whole body vibration exercise. Left is rotational WBV; Right is vertical WBV	64
Figure 2.16 - Transmission factors and EMG-activity of vastus medialis at various frequencies	83
Figure 2.17 – Mean \pm standard error of filtered, untransformed EMGrms for concentric and isometric contractions of the gastrocnemius and vastus lateralis during whole body vibration and with no vibration (baseline)	86
Figure 3.1 - Diagram of stairs used for stair mobility assessment.....	97
Figure 3.2 - Galileo vibration platform.....	101
Figure 4.1 – Mean RPE scores for VIB and EX training.....	111
Figure 4.2 – Mean percentage change for knee flexor torque ($\text{N}\cdot\text{m}\cdot\text{kg}^{-1}$) following the training period for all groups.....	115
Figure 4.3 – Mean percentage change for knee flexor power ($\text{Watts}\cdot\text{kg}^{-1}$) following the training period for all groups.....	115
Figure 4.4 – Mean percentage change for knee extensor torque ($\text{N}\cdot\text{m}\cdot\text{kg}^{-1}$) following the training period for all groups.....	116
Figure 4.5 – Mean percentage change for knee extensor power ($\text{Watts}\cdot\text{kg}^{-1}$) following the training period for all groups.....	116
Figure 4.6 – Mean percentage change for ankle plantar flexor torque ($\text{N}\cdot\text{m}\cdot\text{kg}^{-1}$) following the training period for all groups	119
Figure 4.7 – Mean percentage change for ankle plantar flexor power ($\text{Watts}\cdot\text{kg}^{-1}$) following the training period for all groups	119
Figure 4.8 - Joint torque percentage change between the pre and post test.....	121
Figure 4.9 – Mean individual percentage change following the training period for TUG test for all groups	123

Figure 4.10 – Mean percentage change for 5 m fast walk following the training period for all groups.	124
Figure 4.11– Mean percentage change for 10 m fast walk following the training period for all groups	125
Figure 4.12 – Mean percentage change for STS test following the training period for all groups	126
Figure 4.13 – One-legged postural steadiness vertical force variability percentage change	130
Figure 4.14 – One-legged postural steadiness lateral force variability percentage change	130
Figure 4.15 – Individual one-legged postural steadiness vertical force variability percentage changes for VIB group.....	131
Figure 6.1 - Gastrocnemius electrode placement represented by the X	165
Figure 6.2 - Soleus electrode placement represented by the X.....	165
Figure 6.3 – Tibialis anterior electrode placement represented by the X	166
Figure 6.5 - Vastus medialis electrode placement represented by the X.....	166
Figure 6.4 - Rectus femoris electrode placement represented by the X	167
Figure 6.6 - Biceps femoris electrode placement represented by the X	167
Figure 6.7 - Iliopsoas electrode placement represented by the X.....	168
Figure 6.8 - Gluteus maximus electrode placement represented by the X	168
Figure 6.9 - Peak spectral density of the Vastus Medialis EMG signal during WBV.....	171
Figure 7.1 - Mean increase in neuromuscular activity for each individual muscle collapsed across body positions with WBV	179

Figure 7.2 - Mean increase in neuromuscular activity for the gastrocnemius across body positions	182
Figure 9.1 - Gastrocnemius - medial head electrode placement.	203
Figure 9.2 – Body position set-up for WBV exercise.....	207
Figure 10.1 – Blisters on the right and left foot respectively.....	213
Figure 10.2 – Erythema of the calf musculature following WBV exercise.....	214
Figure 10.3 – Average isometric plantar flexor strength percentage change from the pre-test.....	217
Figure 10.4 – Average isokinetic plantar flexor strength percentage change from the pre-test.....	219

List of Abbreviations

ABS	Australian Bureau of Statistics
AGS	American Geriatric Society
ADL	Activities of daily living
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
ATP_{ase}	Adenosine triphosphatase
bpm	Beats per minute
CONT	Control group
cm	Centimeter
CNS	Central nervous system
CSA	Cross sectional area
DLLE	Dynamic lower limb exercises
EMG	Electromyography
EMG_{rms}	Electromyography root mean square
ES	Effect size
EX	Group undertaking exercise without vibration training
F_{med}	Median frequency
g	Gravitational force - Earth's gravitational acceleration at sea level
GTO	Golgi tendon organ
Hz	Hertz
ICC	Intraclass correlation coefficient
ISO	International Organisation for Standardisation
kg	Kilogram

min	Minute
mm	Millimetre
mM	Millimoles
ms	Milli seconds
mmHg	Millimetres of mercury
Nm	Newton meters
Nm·kg⁻¹	Newton meters per kilogram
OLS	One-legged stance
OLPS	One-legged postural steadiness
r	Correlation
RFD	Rate of force development
ROM	Range of motion
RPE	Rating of perceived exertion
s	Seconds
SD	Standard deviation
SF-36v2	Short form 36 question health survey version two
STS	Sit to stand
SWBK	Standing with bent knees
TEM%	Technical error of measurement percentage
TUG	Timed up and go test
TVR	Tonic vibration reflex
VIB	Group undertaking whole body vibration training
WBV	Whole body vibration
yr	Year
%BW	Percentage of body weight

List of Publications

Sven Rees, Aron Murphy and Mark Watsford (2007). Effects of vibration exercise on muscle performance and mobility in an older population. *Journal of Aging and Physical Activity*, 15(4), 367-381

Sven Rees, Aron Murphy and Mark Watsford (2008). Effects of vibration exercise on postural steadiness in an older population. *Journal of Science and Medicine in Sport*, doi:10.1016/j.jsams.2008.02.002

Sven Rees, Aron Murphy and Mark Watsford (2008). The effects of whole body vibration exercise on lower extremity muscle strength and power in an older population: A randomized clinical trial. *Physical Therapy*, 88(4), 1-9

Conference Presentations

Sven Rees, Aron Murphy, Mark Watsford and Robert Lockie. The effects of vibration training on postural steadiness in a healthy, older population. Australian Association for Exercise and Sports Science Conference, September/October 28-1, 2006

Sven Rees, Aron Murphy, Mark Watsford and Robert Lockie. Effects of vibration exercise on lower limb strength and functional performance in an older population. Congress of the European College of Sport Science, July 11-14, 2007